

Air Circulation and Heat Exchange Under Reduced Pressures

F42-0009-10

*V. Rygalov¹, R. Wheeler², M. Dixon³,
P. Fowler², L. Hillhouse¹*

1 Dept of Space Studies, Univ. of North Dakota, USA

2 NASA Kennedy Space Center, USA

3 University of Guelph, Canada

COSPAR, Bremen, Germany

July 2010

Low Pressure Atmospheres for Space Greenhouses

Benefits of Low Pressure for Greenhouses

- *Minimal gas leakage*
- *Reduced forces on the structure*
- *Less system mass*

Challenges for Low Pressure Settings

- *Plant physiological responses to reduced pressures*
- *Environmental control of greenhouse / chambers*
 - *Material Exchange and Recycling*
 - *Humidity and Thermal Regulation*



Previous Work

○ Plant physiology under reduced pressures

- *Evapotranspiration and water cycles accelerated*
 - *But there is some evidence for acclimation by plants*
- *Minimal pO_2 and pCO_2 levels needed for plant health*
- *Reduced convective heat transfer for leaves*

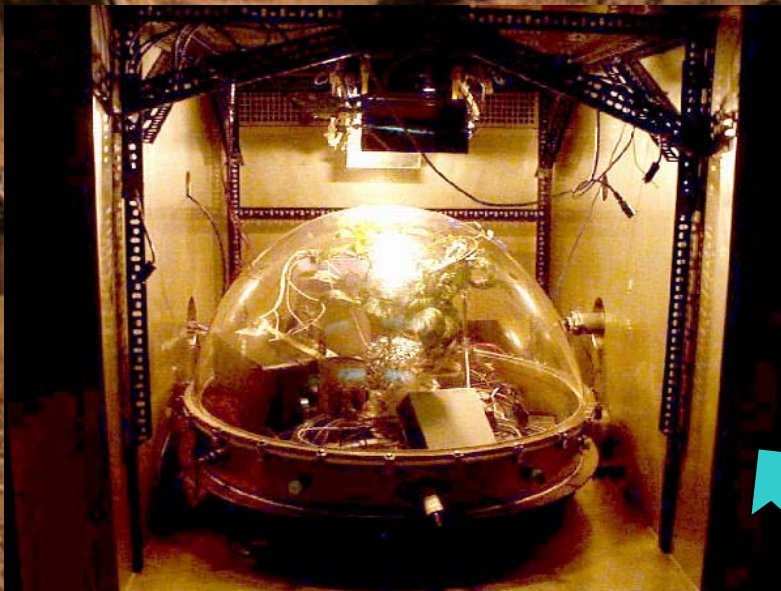
○ Environmental control

- *Changes in Convection*
 - *Reduced Air Density*
 - *Altered Air Velocities*
- *Atmospheric Composition*
 - *Carbon Dioxide*
 - *Oxygen*
 - *Water Vapor*



NASA's Kennedy Space Center's Thermotron

Testing a Pressurized Chamber in a Low Pressure Environment



Pressure Versus Air Velocity

(previous work)

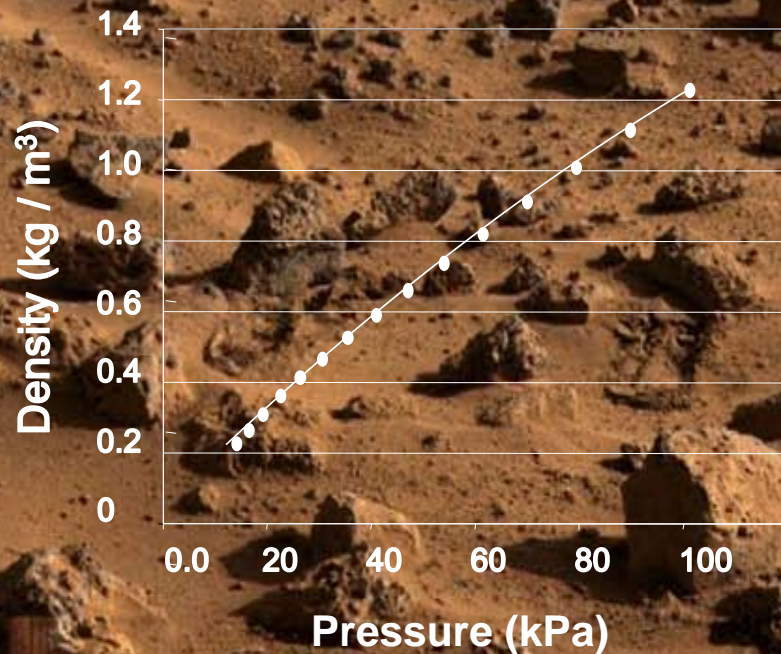


Fig. 1. Comparison of atmospheric density vs. pressure (data from Smithsonian Tables).

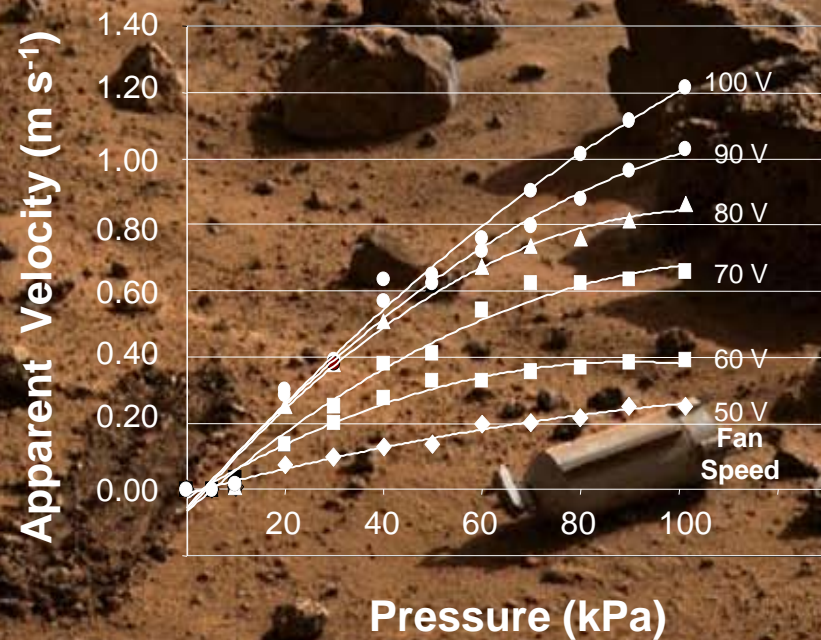


Fig. 2. Effect of pressure and fan speed (voltage) on "apparent" air velocity for mechanical anemometer. Since the anemometer was calibrated at 101 kPa, the outputs are probably indicative of apparent rather than actual air flow.

Thermal cooling tests:

Brass plate ("leaf") heating

- Electrical resistance heater in thermo-insulated container
- Heat raised temp $\sim 3\text{-}5^{\circ}\text{C}$ above ambient
- Temperature of brass plate was measured by thermocouples
 - Temperature on the graphs presented in Volts DC

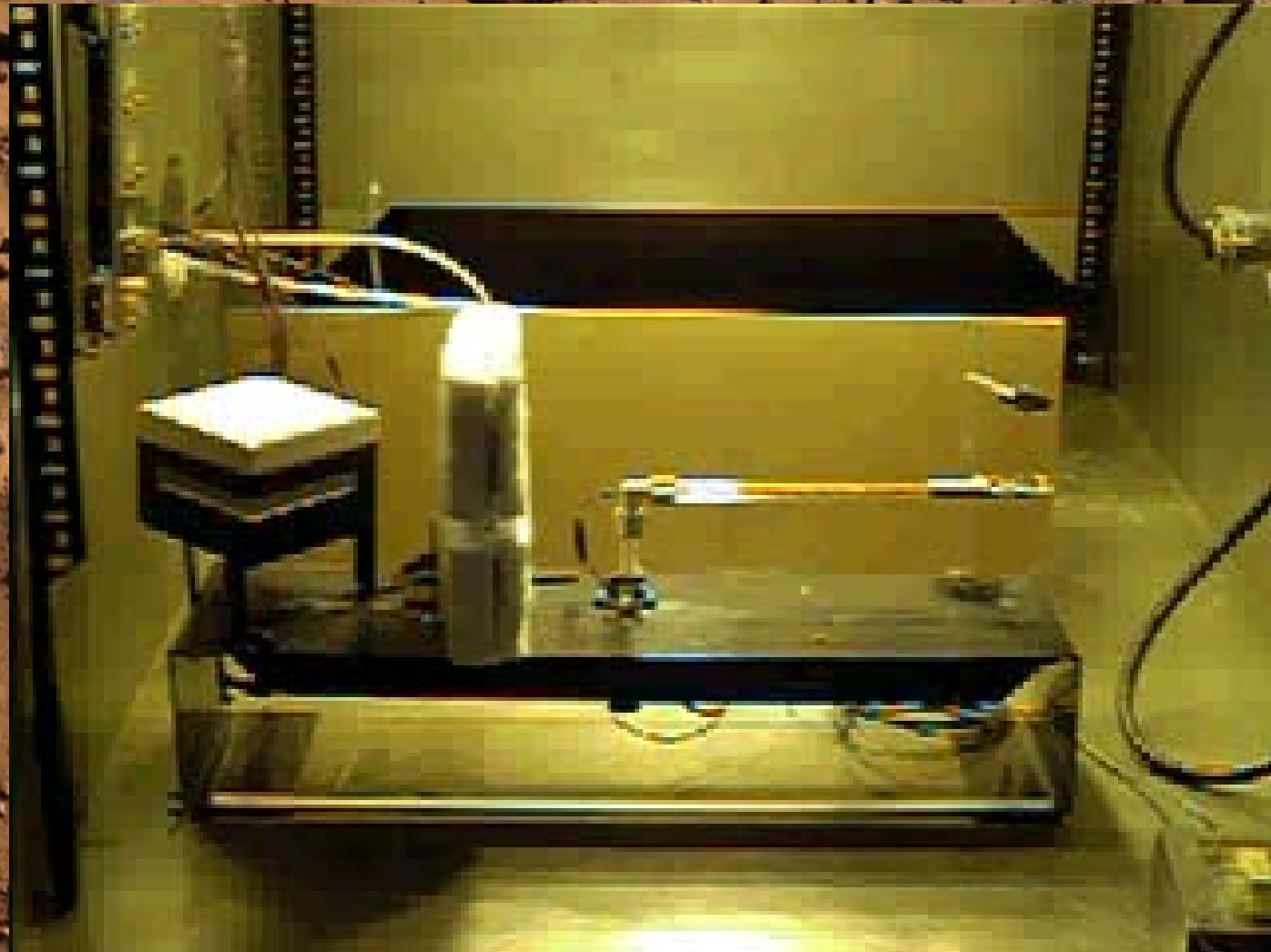
Cooling rates tracked under different pressures

- Heat source was removed and isolated from the brass plate following heating (to eliminate radiative exchange)
- Pressures tested ranged 101.3 kPa (normal atmosphere) to 4 kPa with steps of 10 kPa

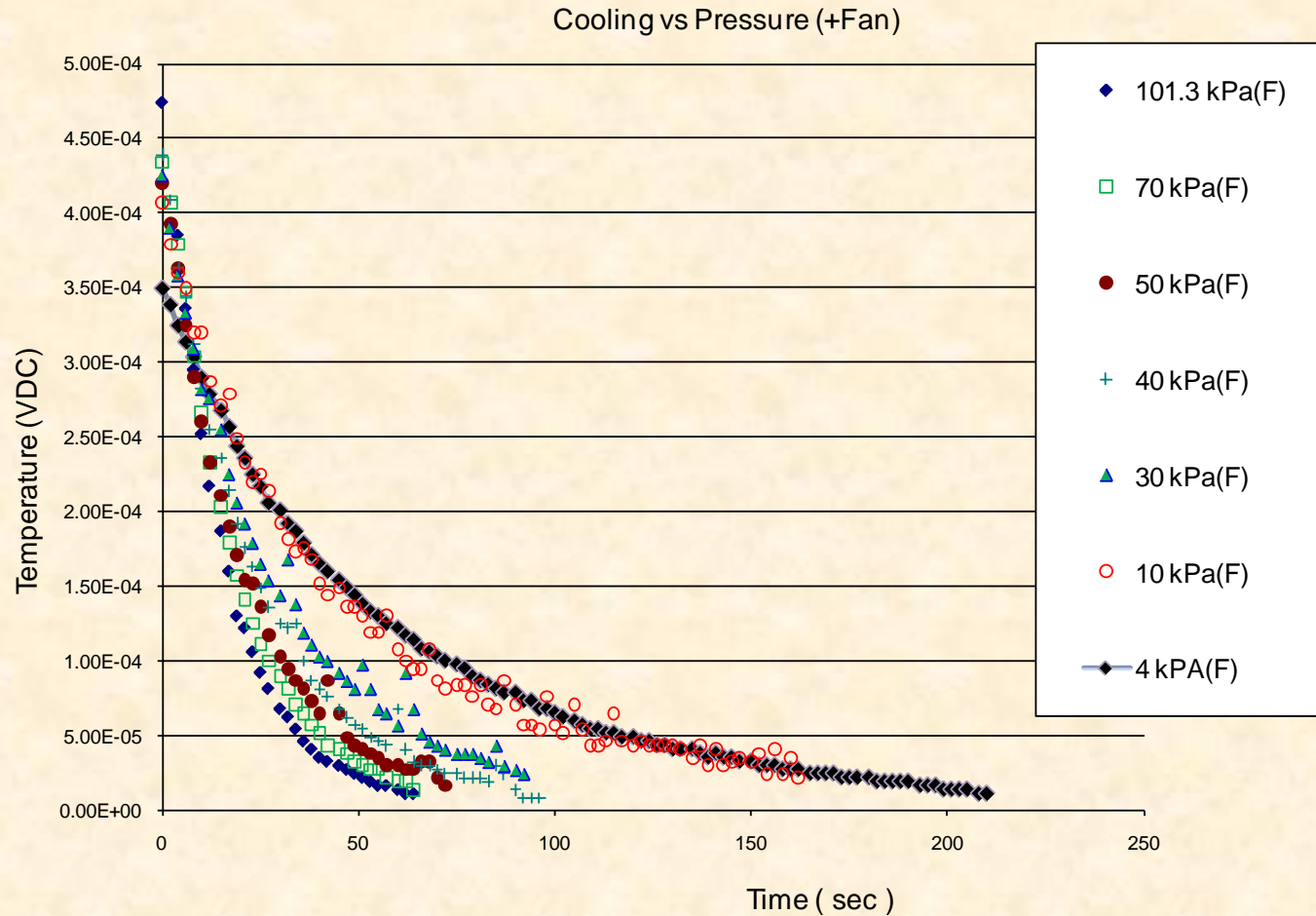
Air circulation regimen

- Free convection around brass plate (fan off)
- Forced convection (fan on)

Thermal Cooling Test Set Up and Arrangements



Cooling Curve Data



Activated convective heat exchange with fan on

Aerodynamic resistance

Cooling curve technique

$$r_a = \frac{\rho C_p A}{b w m}$$

r_a = aerodynamic resistance

ρ = density of air

C_p = specific heat of air

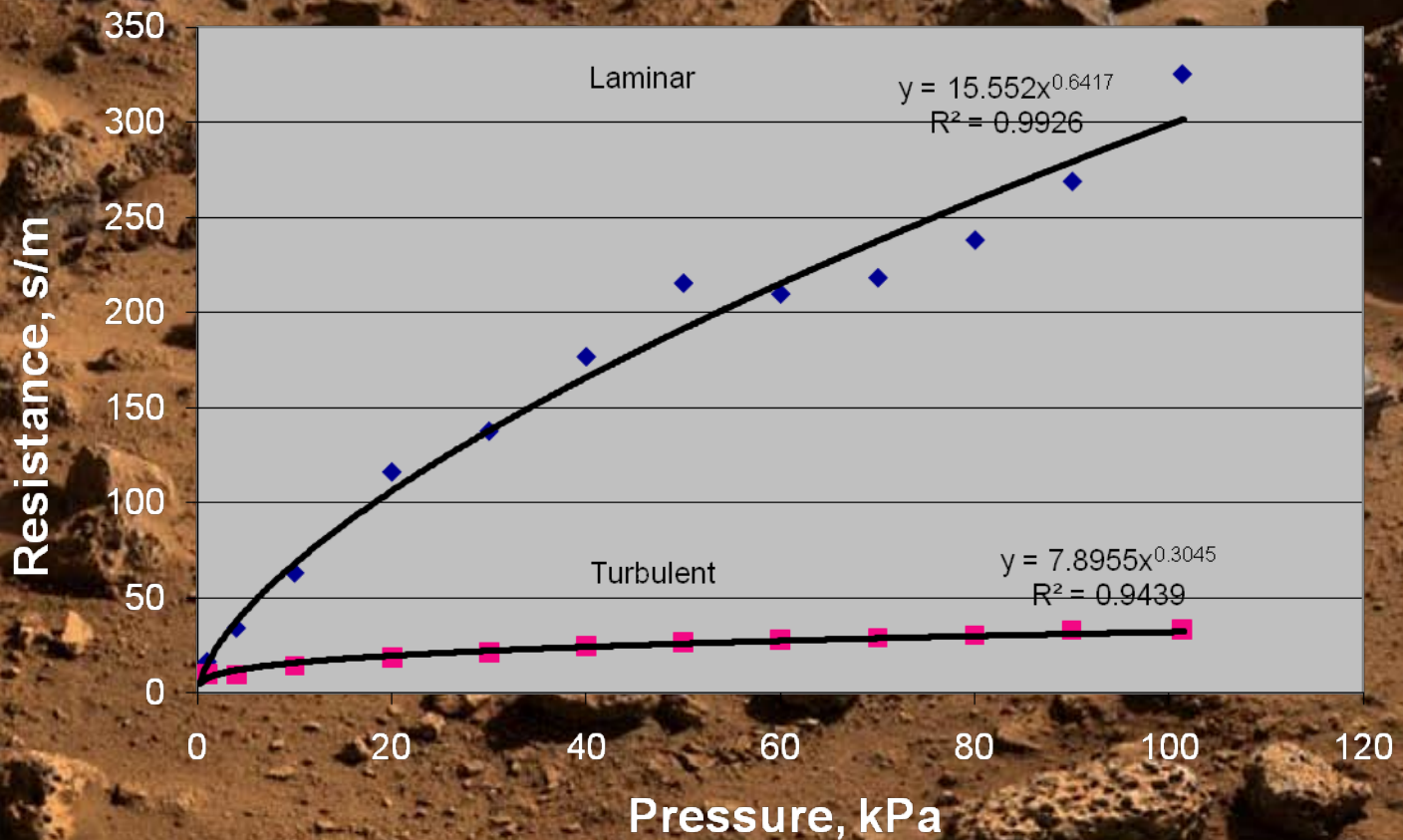
A = area of leaf

b = specific heat of brass

w = mass of leaf

m = slope of cooling curve

Boundary Layer Heat Resistance vs Pressure



Conclusions

- Heat exchange rates decrease non-linearly with reductions in atmospheric pressure
- This decrease creates risk of thermal stress (elevated leaf temperatures) for plants under reduced pressures
- Forced convection (fans) significantly increases heat exchange rate under almost all pressures except below ~ 10 kPa
- Plant cultivation techniques under reduced pressures will require forced convection

Conclusions *(continued)*

- The cooling curve technique is a reliable means of assessing the influence of environmental variables like pressure and gravity on gas exchange of plant.
- These results represent the extremes of gas exchange conditions for simple systems under variable pressures.
- In reality, dense plant canopies will exhibit responses in between these extremes.

Future Directions

- More research is needed to understand the dependence of forced convection on atmospheric pressure
- The overall thermal balance model should include latent and radiative exchange components.



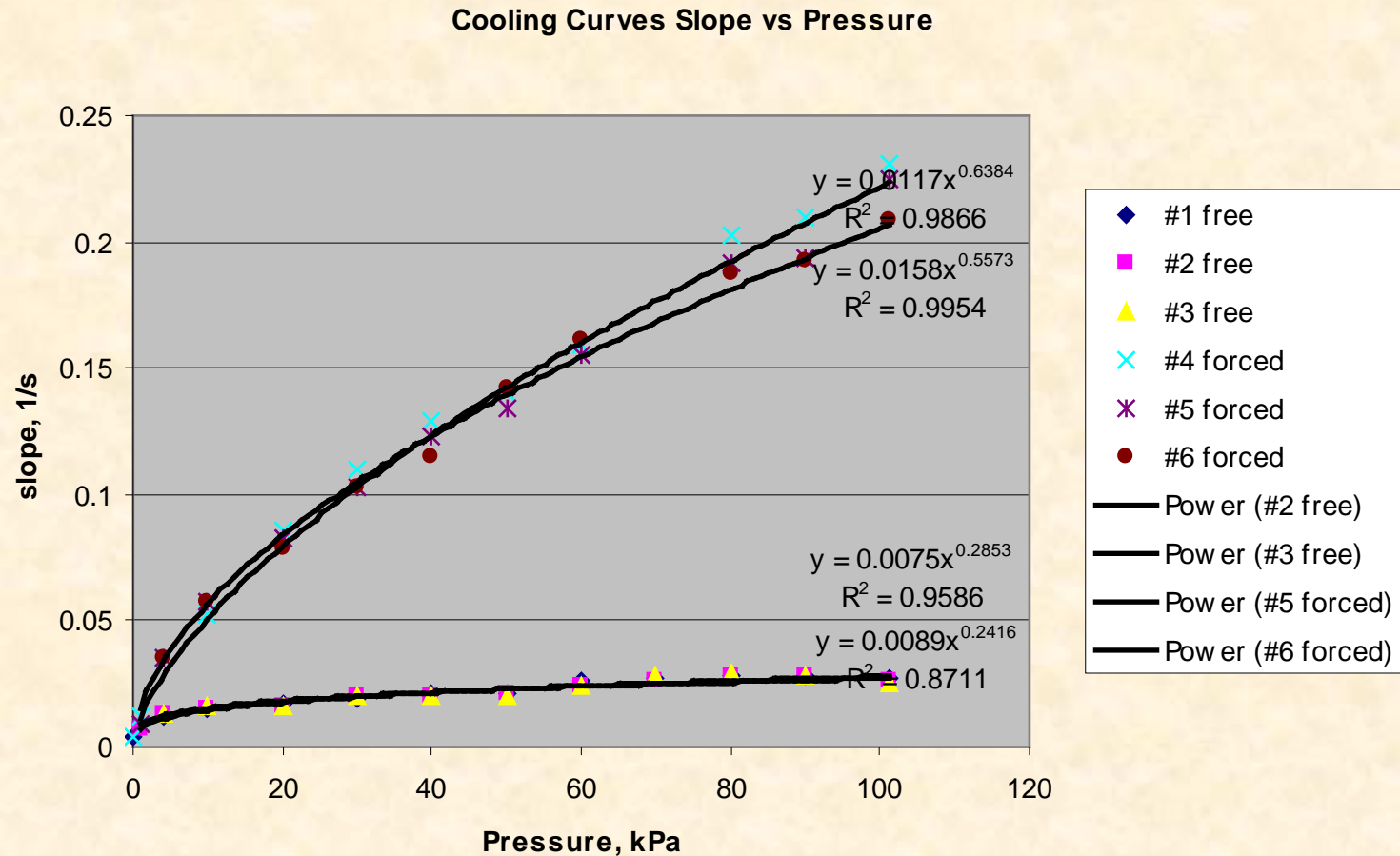
Questions?



Appendix: nomenclature...

T	=	temperature of brass model (C or K);
T_a	=	temperature of air (C or K);
A	=	area of surface of brass model (m ²);
w	=	mass of brass (kg);
b	=	specific heat of brass (J/kg);
C_p	=	specific heat of air (J/kg);
ρ	=	air density (kg/m ³);
σ	=	Stefan - Boltzman constant (J/C ⁴ /m ² /s);
ε	=	emissivity (nd);
α	=	absorptivity (nd);
R_H	=	boundary layer heat resistance for free convection (s/m);
F	=	air exchange rate near brass (m ³ /sec);
V	=	volume of the experimental system (m ³);
h	=	thickness of the boundary layer (m)

Heat Exchange Rate vs. Pressure



Math Schematics

- Exponential approximation for temperature differential (brass plate ~ air)

$$\frac{d}{dt}(T - T_a) = -(m_H + m_F + m_R) \cdot (T - T_a) = -m \cdot (T - T_a)$$

- Free convection slope m_H is directly proportional air density ρ and consequently pressure

$$m_H = \frac{\rho \cdot C_p \cdot A}{b \cdot w \cdot R_H}$$

- Forced convection slope m_F is directly proportional air density ρ and pressure

$$m_F = \frac{\rho \cdot C_p \cdot A \cdot h}{b \cdot w} \cdot \frac{F}{V}$$

Theoretical considerations

- Three major heat exchange components can be approximated by first degree differential equation
 - Free convection (disappears as pressure drops)
 - Forced convection (disappears as pressure drops)
 - Irradiative exchange (small but increases relatively as pressure drops)
- Solutions for differential equation
 - Exponent
 - When presented in logarithmic coordinates slope could be calculated
 - Line slope characterizes rate of heat exchange
- Calculations for free and forced convections (fan off and on)

Radiative cooling

- Radiative cooling curve slope m_R does not depend on pressure and is a ultimate (minimal) slope for exponential heat exchange in rarified atmospheres

$$m_R = \frac{4 \cdot \sigma \cdot \varepsilon \cdot A}{b \cdot w} \cdot (T_a)^3$$